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Der Präsident des Europäischen Patentamts;  
Im Auftrag

For the President of the European Patent Office

Le Président de l'Office européen des brevets  
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ELECTROCHEMICAL ELEMENT FOR USE AT HIGH TEMPERATURES

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ELECTROCHEMICAL ELEMENT FOR USE AT HIGH TEMPERATURES

BACKGROUND OF THE INVENTION

This invention relates to an electrochemical element for use at high temperatures.

Electrochemical elements comprise a cathode and an anode,  
5 and an electrolyte which is arranged between the cathode and the anode. The cathode and anode generally comprise metallic current collectors and an active material, which can be the current collector material itself. An  
10 electrochemical cell that produces electricity as a result of a spontaneous chemical reaction is called a galvanic cell. An electrochemical element or cell in which a non-spontaneous chemical reaction is driven by an external current source is called an electrolytic cell.

An electrolyte is a compound, or combination of  
15 compounds, capable of conducting electricity in the form of an ionic current, carried by mobile ions. Examples of an electrolyte are a salt, or a mixture of salts, in its solid or molten state or dissociated into its ions in a solvent in which the solvent is not or only slightly  
20 dissociated.

Electrochemical elements may be configured as a primary battery or a rechargeable battery or an electrochemical capacitor. Rechargeable batteries are often referred to as secondary batteries and non-  
25 rechargeable batteries are often referred to as primary batteries.

A battery is a device that stores electrical energy using one or more electrochemical cells. The cells can be

connected in series or parallel. The physical construction of a cell is such that a direct reaction of the chemicals stored in the electrodes is prohibited by physically separating the electrodes by an electrolyte.

5 When the two electrodes are connected through an external circuit, a galvanic cell will produce an electrical current. Electrons will flow through the external circuit, ions will flow through the electrolyte.

10 The reactions at the electrodes, involving transfer of electrons from one substance to another and thus the reduction and oxidation of the substances, are called redox reactions. The electrode where oxidation takes place is called the anode, the electrode where reduction takes place is called the cathode.

15 A rechargeable battery is a battery or electrochemical cell in which the chemical reaction, producing the electrical current upon discharge, is easily chemically reversible. A rechargeable battery can be recharged by applying an electrical current to its  
20 electrodes or terminals. Preferably, a rechargeable battery can be recharged hundreds of times without significant loss of storage capacity. A primary battery can be discharged only once and has to be disposed off afterwards.

25 The active material of the positive electrode in a primary battery will be reduced in the discharge process and is therefore also known as the cathode material. Vice versa is material at the negative electrode known as the anode material. The same naming convention is used for  
30 the active materials of a rechargeable battery in its charged state (a galvanic cell).

Batteries are widely used as a source of electrical energy for a variety of applications. Rechargeable

batteries are used for many applications to avoid the replacement and disposal of primary batteries. Moreover, their use allows the remote operation of devices in difficult to reach locations where exchange of primary batteries is not practically possible but where recharging a battery would be feasible. An example of such a location is in a wellbore for oil and gas production. Not only are downhole locations difficult to reach, the environmental conditions are also harsh with temperatures in the range of 60 to 200 °C which demands an electrochemical element suitable for high temperatures.

Most batteries are configured for use in a specified temperature range, which is typically capped due to instability, disintegration, melting and/or evaporation of the chemical compounds in the battery above a certain temperature. A typical operating range for batteries is between -40 and +60 °C.

Many rechargeable battery chemistries have been developed. Examples are lead-acid, nickel-cadmium, nickel-metalhydride, and lithium (lithium-metal and lithium-ion) batteries. From these, batteries based on lithium chemistry are most interesting since they offer the highest energy density because lithium has the lowest reduction potential known (-3 V versus a standard hydrogen electrode) and has a high specific storage capacity of 3828 mAh/g (for a Lithium 7 isotope= $\text{Li}^7$ ). However, the formation of lithium dendrites on the lithium anode in rechargeable batteries with electrolytes based on organic solvents has been a safety concern. This has led to the development of lithium-ion batteries (Li-ion) in which the lithium anode has been replaced with an intercalation material.



An intercalation or insertion compound is a host compound in which a guest species can be stored or from which it can be extracted. Examples of three dimensional intercalation materials are  $\text{LiMn}_2\text{O}_4$  and  $\text{Li}_4\text{Ti}_5\text{O}_{12}$  which  
5 reversibly allow the extraction and re-insertion of lithium ions as guest species from their cubic crystal lattice structures.

An intercalation reaction or insertion reaction is defined as a reaction, generally reversible, that  
10 involves the introduction of a guest species into a host structure without a major structural modification of the host. In the strictest sense, intercalation refers to the insertion of a guest into a two-dimensional host; however, the term also now commonly refers to one-  
15 dimensional and three-dimensional host structures. An example is the insertion of lithium into layered  $\text{TiS}_2$ :  
$$x \text{ Li} + \text{TiS}_2 \rightarrow \text{Li}_x\text{TiS}_2 \quad (0 \leq x \leq 1)$$
 (this example is described in the IUPAC Compendium of Chemical Terminology, 2nd Edition, 1997).

20 The current state-of-the-art lithium and Li-ion batteries comprise positive electrode (cathode) materials like  $\text{MnO}_2$ ,  $\text{LiCoO}_2$ ,  $\text{LiNi}_{0.8}\text{Co}_{0.2}\text{O}_2$ , and  $\text{LiMn}_2\text{O}_4$ . Carbonaceous materials like graphite, MCMB, and petroleum coke are used as negative (anode) materials in Li-ion  
25 batteries. The resulting batteries show attractive high voltages between 3 and 4 V.

The electrolytes used in these batteries are based on lithium salts as  $\text{LiPF}_6$ ,  $\text{LiBF}_4$ ,  $\text{LiClO}_4$ , and  $\text{LiAsF}_6$  dissolved in (mixtures of) organic solvents like for  
30 example ethylene-carbonate (EC), di-methyl-carbonate (DMC), propylene-carbonate (PC), ethyl-methyl-carbonate (EMC) etc. These solvents are flammable and show considerable vapour pressures at temperatures above

60 °C. Furthermore, these electrolytes can strongly react with the other battery components if the battery temperature rises above 60 °C, for example in the case of over charging or internal shorting, imposing a potential danger. The operating temperature range is therefore limited from about -40 °C to +80 °C, which is similar to that found for the aqueous electrolytes.

Rechargeable battery chemistries that are able to operate at higher temperatures can be found in the molten salt systems, for example the system Li//FeS<sub>2</sub> which, depending on the composition of the electrolyte, operates between 350 and 550 °C, or the system Na//S which operates between 220 and 350 °C. Therefore, there is a gap in the operating temperature range of current rechargeable battery technology between about 80 and 220 °C. The reason for this gap lies in the inadequate thermal properties of the available electrolytes.

The current technology of primary batteries, however, does not show such a temperature gap. The system Li//SO<sub>2</sub>Cl operates between -40 and +150 °C or, by alloying lithium with Magnesium, between 70 to 200 °C. In this battery chemistry the electrolyte is the in-situ reaction product when lithium metal contacts SO<sub>2</sub>Cl.

WO 01/15258 (D.R. MacFarlane et al.) discloses a solid state conductive material comprising a pyrrolidinium or other cation. It further discloses that an anode of a lithium battery may comprise a lithium intercalation material.

Recent advances in the research of so called ionic liquids have shown that these materials have very promising properties to be used for a new generation of battery electrolytes, especially for high temperature batteries. Ionic liquids are known and have gained a lot

of attention for their suitability in green chemistry. In contrast to the organic solvents, ionic liquids are non-flammable, non-volatile, and are chemically stable over a wide temperature range, up to 400 °C. Furthermore, they can be mixed with a wide range of electrolyte salts, allowing very high electrolyte salt concentrations. The conductivities of these electrolytes is comparable or sometimes higher than comparable organic solvent based systems. Many of the ionic liquids are in their liquid state in a wide temperature range, starting below room temperature and ranging up to about 400 °C.

An article by D.R. MacFarlane, *et al.*, (Journal of Phys. Chem. B, 103 (20) 1999, 4164) discloses that, among the known ionic liquids, some members of the pyrrolidinium family of ionic liquids show the widest electrochemical stability windows of up to 5.5 V. Therefore, this family is especially interesting for the application in electrolytes for high temperatures.

It is known that ionic liquids may be used as an electrolyte in electrochemical elements if an electrolyte salt (e.g. a lithium salt) is added to the ionic liquid in order to obtain ionic conductivity of the required ion. The term ionic liquid is not well defined in literature but refers in general to a molten salt or to a liquid which consists of fully or almost fully dissociated ions. Room temperature ionic liquids are thus ionic liquids that are in the liquid state at room temperature. 'Room temperature' is often defined as a temperature close to 25 °C but can be as high as 80 °C. It has to be noted therefore that not all compounds classified as 'ionic liquids' in the open literature have a melting point below 80 °C.

In this specification and claims ionic liquids are defined as 'ionic compounds', which are liquid in the operating temperature range. An ionic liquid may comprise a liquid mixture of ionic compounds.

5 It is known that in electrochemical elements that are configured for use at temperatures below 60 °C the electrolyte layer may comprise an extensive range of materials with ionic conductivity, such as electrolyte solutions comprising salts, which are dissociated into  
10 ions when dissolved in a solvent.

US patent 5,827,602 (Covalent Associates, Inc.) discloses the hydrophobic ionic liquids based on cations comprising pyridinium, pyridazinium, pyrimidinium, pyrazinium, imidazolium, pyrazolium, thiazolium,  
15 oxazolium, and triazolium. Also disclosed is the use of these ionic liquids in an electrochemical cell or a capacitor. No evidence of a stable functioning rechargeable battery incorporating these ionic liquids is shown and no operating temperature range is claimed.

20 US patent 5,965,054 (Covalent Associates, Inc.) discloses the use of the hydrophobic ionic liquids based on cations comprising pyridinium, pyridazinium, pyrimidinium, pyrazinium, imidazolium, pyrazolium, thiazolium, oxazolium, and triazolium in an electrolyte  
25 with a salt dissolved in a polar organic liquid or dissolved in liquid sulfur dioxide. The use of a polar solvent renders the known electrolyte not suitable for high temperature applications due to vapour formation. No evidence of a stable functioning rechargeable battery  
30 incorporating these ionic liquids is shown and no operating temperature range is claimed.

US patent 6,326,104 (Electrochemical Systems, Inc.) discloses the use of electrolytes based on ionic liquids

comprising the pyrazolium cation. This prior art reference provides four examples related to lithium rechargeable batteries (a  $\text{LiMn}_2\text{O}_4$  cathode and a lithium metal anode), wherein one cell was tested at 55 °C and three cells were tested at room temperature. All cells showed lower than expected capacities and/or fading, i.e. only an indication is given of the potential use. Also, a description was given that the following ionic liquids were not stable against metallic lithium: 1-ethyl-3-methyl-imidazolium-tetrafluoroborate and 1,2-dimethyl-3-propylimidazolium-tetrafluoroborate.

US patent 5,855,809 (Arizona Board of Regents) discloses the use of electrolytes based on the following ionic liquids:  $\text{X}_3\text{PNPOX}_2$ ,  $\text{X}_3\text{PNCH}_3$ ,  $\text{X}_3\text{PNSO}_2\text{X}$ ,  $\text{XSO}_2\text{CH}_3$ ,  $\text{CH}_3\text{COX}$ , and  $\text{CH}_3\text{CH}_2\text{NPX}_3$  where X is a halogen atom. The results of one battery test are shown for a cell comprising a  $\text{LiMn}_2\text{O}_4$  cathode and a lithium metal anode with  $0.3\text{LiAlCl}_4$  in  $0.7(\text{AlCl}_4^-/\text{SO}_2\text{NPCl}_3^+)$  as the electrolyte. However, FIG 16 in this patent is not showing the known voltage profile as function of x for a cell with a  $\text{Li}_x\text{Mn}_2\text{O}_4$  ( $0 \leq x \leq 1$ ) cathode and a lithium metal anode. Moreover, the charge capacity is twice the discharge capacity which means that the efficiency is poor. It was further indicated that this cell behaviour was reversible over 50 cycles.

US patent 6,552,843 (Innovative Technology Licensing LLC) discloses a reversible electrodeposition device for controlling the propagation of electromagnetic radiation comprising an electrolyte based on ionic liquids comprising a cation based on N-methyl-pyrrolidinium, pyrrolidinium, 1-ethyl-3-methyl-imidazolium, 1-N-butyl-pyridinium, 2-methyl-1-pyrrolinium or 1-ethyl-

imidazolium. A reversible electrodeposition device is an electrochemical device that can only operate as an electrolytic cell. Furthermore, the electrodes do not contain intercalation materials.

5 International patent application WO 02/063073 (B.R. Mattes, W. Lu) discloses the use of ionic liquids in electrochemical devices with conjugated polymers as the active materials in the electrodes. The cation of the ionic liquid is based on pyridinium, pyridazinium, 10 pyrimidinium, pyrazinium, imidazolium, pyrazolium, thiazolium, oxazolium, triazolium, ammonium, pyrrolidinium, pyrrolinium, pyrrolium, and piperidinium. Conjugated polymers are polymer materials with alternating single and double bonds along the polymer 15 chain. No battery related data are disclosed in this prior art reference.

Electrochemical elements for use at a temperature above +60 °C are known from International patent applications WO 0180344 and WO 0209215. The known 20 electrochemical elements comprise a granular electrolyte layer, which is substantially free of polymer binder materials that would evaporate at an elevated temperature. A disadvantage of the use of a granular electrolyte layer is that the physical contact surfaces 25 between the granules are relatively small, which results in a limited transfer of ions via the granules between the cathode and anode, and in a moderate electric power output of the element. The batteries known from these prior art references are suitable for use at a 30 temperature up to about 100 °C and have a limited output of electric power, which is expected to be a result of the limited contact areas between the solid state particles in the electrolyte.

It is an object to provide an electrochemical element which is suitable for use at a high temperature.

It is a further object of the present invention to provide an electrochemical element which is suitable for use as a rechargeable battery, which can be used as an efficient energy source at a temperature above 50 °C, in particular in the range from 60 to 150 °C.

It is a further object of the present invention to provide a method for generating electrical energy by means of a rechargeable battery in an underground wellbore, such as an oil or gas production well, in which the temperature may be between 60 and 200°C or a geothermal well in which the temperature may be up to several hundred degrees Celsius.

#### SUMMARY OF THE INVENTION

The electrochemical element according to the invention comprises a cathode, an anode and an electrolyte arranged between the cathode and anode, which electrolyte comprises an ionic liquid comprising an anion and a cation, which cation comprises a pyrrolidinium ring structure; and wherein the active material of the cathode comprises an intercalation material.

It is observed that WO 01/15258 discloses a solid state conductive material comprising a pyrrolidinium or other cation. It further discloses that an anode of a lithium battery may comprise a lithium intercalation material.

It is believed that a solid state conductive material has a lower ionic conductivity than a ionic liquid. The use of a ionic liquid in the electrochemical element according to the present invention instead of a solid state conductive material will result in a higher power

density and therefore in a better performance of the electrochemical element.

When used in this specification and claims an active intercalation material is defined as an intercalation material that takes part in the redox reaction in the electrodes

As an alternative to the use of an active intercalation material the anode of an electrochemical element may comprise a conjugated polymer. International patent application WO/02/063073 discloses an electrochemical element with an anode or cathode comprising a conjugated polymer as the major constituent of the active material.

The electrochemical element according to the invention may be configured for use as a primary or a rechargeable battery or an electrochemical capacitor at high temperature, such as a temperature above 50 °C and particularly at a temperature between 60 and 150 °C. It is furthermore preferred that the pyrrolidinium ring structure has the formula: N-R<sub>1</sub>-N-R<sub>2</sub>-pyrrolidinium, wherein R<sub>1</sub> and R<sub>2</sub> are alkyl groups and that R<sub>1</sub> is methyl and R<sub>2</sub> is butyl or hexyl.

The anion of the ionic liquid preferably comprises any of the following compounds:

- ClO<sub>4</sub><sup>-</sup>, AsF<sub>6</sub><sup>-</sup>, PF<sub>6</sub><sup>-</sup>, BF<sub>4</sub><sup>-</sup>, a halogen ion, N(CF<sub>3</sub>)<sub>2</sub><sup>-</sup>, N(CF<sub>3</sub>SO<sub>2</sub>)<sub>2</sub><sup>-</sup>, CF<sub>3</sub>SO<sub>3</sub><sup>-</sup>, and N(CH<sub>3</sub>SO<sub>2</sub>)<sub>2</sub><sup>-</sup>, N(C<sub>2</sub>F<sub>5</sub>SO<sub>2</sub>)<sub>2</sub><sup>-</sup>.

It is also preferred that the alkali salt comprises a lithium salt which may comprise any of the following compounds:

- LiN(CF<sub>3</sub>SO<sub>2</sub>)<sub>2</sub>, LiCF<sub>3</sub>SO<sub>2</sub>, LiClO<sub>4</sub>, LiBF<sub>4</sub>, LiPF<sub>6</sub>, and LiAsF<sub>6</sub>.



Alternatively the alkali salt may comprises  $\text{MgCF}_3\text{SO}_2$  or  $\text{Mg}(\text{ClO}_4)_2$ .

The cathode suitably comprises  $\text{Li}_4\text{Ti}_5\text{O}_{12}$ ,  $\text{LiCrTiO}_4$ ,  $\text{TiS}_2$  or  $\text{Li}_{1-y}\text{M}_y\text{FePO}_4$ , where  $\text{M}=\text{Mg}$ ,  $\text{Nb}$ ,  $\text{Zr}$ ,  $\text{Ti}$  or  $\text{Al}$  (0 $\leq y\leq 0.02$ ), as the active material and as the major constituent by mass.

The anode suitably comprises lithium as the active material.

The invention also provides a method of providing electrical energy in an underground wellbore, wherein the energy is provided by an electrochemical element according to the invention. The underground wellbore may form part of an oil and/or gas production well or a geothermal well.

#### BRIEF DESCRIPTION OF THE DRAWINGS

The invention will be described in more detail with reference to the accompanying drawings wherein:

FIG. 1 A,B and C depict three examples of pyrrolidinium cations comprising a ring structure of four Carbon atoms and one Nitrogen atom;

FIG. 2 is a graph showing charge and discharge capacity of the cell with a  $\text{Li}_4\text{Ti}_5\text{O}_{12}$  cathode and a lithium metal anode 110 °C with LiTFSA in P<sub>14</sub>TFSA in the molar ration 0.38:0.62. The capacity is given as percentage of the expected sample capacity based on the active mass and theoretical capacity;

FIG. 3 is a graph showing voltage curves for cycle number 7, 107 and 207 of the cell with a  $\text{Li}_4\text{Ti}_5\text{O}_{12}$  cathode and a lithium metal anode 110 °C with LiTFSA in P<sub>14</sub>TFSA in the molar ration 0.38:0.62.;

FIG. 4 is a graph showing charge and discharge capacity of the cell with a  $\text{Li}_4\text{Ti}_5\text{O}_{12}$  cathode and a

lithium metal anode 110 °C with 2.0 mol/kg LiTFSA in P<sub>16</sub>TFSA. The capacity is given as percentage of the expected sample capacity based on the active mass and theoretical capacity;

5        FIG. 5 is a graph showing charge and discharge capacity of the cell with a TiS<sub>2</sub> cathode and a lithium metal anode 110 °C with LiTFSA in P<sub>14</sub>TFSA in the molar ration 0.40:0.60. The capacity is given as percentage of the expected sample capacity based on the active mass and  
10        theoretical capacity;

FIG. 6 is a graph showing voltage curve for cycle 50 of the cell with a TiS<sub>2</sub> cathode and a lithium metal anode 110 °C with LiTFSA in P<sub>14</sub>TFSA in the molar ration 0.40:0.60;

15        FIG. 7 is a graph showing charge and discharge capacity of the cell with a LiCrTiO<sub>4</sub> cathode and a lithium metal anode 150 °C with LiTFSA in P<sub>14</sub>TFSA in the molar ration 0.05:0.95. The capacity is given as percentage of the expected sample capacity based on the  
20        active mass and theoretical capacity;

#### DETAILED DESCRIPTION OF THE INVENTION

FIG.1A depicts that a pyrrolidinium compound comprises a positively charged ring structure of four carbon atoms and one nitrogen atom. The depicted compound  
25        has the formula: N-R<sub>1</sub>-N-R<sub>2</sub>-pyrrolidinium, wherein R<sub>1</sub> and R<sub>2</sub> are alkyl groups. In the electrochemical element according to the invention is it preferred that R<sub>1</sub> is methyl and R<sub>2</sub> is butyl or hexyl.

FIG. 1B depicts the chemical structure of 1-butyl-1-methylpyrrolidinium and FIG.1C depicts the chemical  
30        structure of 1-butyl-2,2,3,3,4,4,5,5-octafluoro-1-methyl-pyrrolidinium.

Several rechargeable batteries with electrolytes comprising pyrrolidinium based ionic liquids were made and tested using the manufacturing and testing procedures that are described hereinbelow. Electrolytes were synthesised by mixing pyrrolidinium based ionic liquids and lithium salts. The following acronyms will be used:

P<sub>14</sub>=1-methyl-1-butyl-pyrrolidinium

P<sub>16</sub>=1-methyl-1-hexyl-pyrrolidinium

TFSA=bis(trifluoromethylsulfonyl)amide= $\text{N}(\text{CF}_3\text{SO}_2)_2^-$

P<sub>14</sub>TFSA and P<sub>16</sub>TFSA (acquired from Merck KGaA) were dried under dynamic vacuum at 90 °C for 48 hours. The salts LiTFSA ( $\text{LiN}[\text{CF}_3\text{SO}_2]_2$ , 3M) and lithium-perchlorate ( $\text{LiClO}_4$ , from Alfa Aesar) were dried under dynamic vacuum at 130 °C for 48 hour. After being dried, the materials were transferred into a helium filled glovebox (water content <5 ppm). The following electrolytes were made by mixing the appropriate amounts of ionic liquid and salt:

5 mol% LiTFSA in P<sub>14</sub>TFSA

0.38 mol LiTFSA in 0.62 mol P<sub>14</sub>TFSA

2.0 mol/kg LiTFSA in P<sub>16</sub>TFSA

1.0 mol/kg  $\text{LiClO}_4$  in P<sub>14</sub>TFSA

Electrodes were made of  $\text{LiCrTiO}_4$ ,  $\text{Li}_4\text{Ti}_5\text{O}_{12}$  and  $\text{TiS}_2$  and were coated as follows.

The electrodes were made by the doctor-blade technique on aluminium or copper foil current collectors using a paste of the active materials. The pastes contained typically 80 w% active material, 10-13 w% conductive additives, and 7-10 w% of a binder dissolved in 1-methyl-2-pyrrolidone (Merck KGaA). The conductive additives were a mixture of carbon black (2-10%, SuperP from MMM) and graphite (0-10 w%, KS4 from Timcal). The binder was either polyvinylidene fluoride (PVDF, from

Solvay) or polymethylmethacrylate (PMMA, from XXX).  
LiCrTiO<sub>4</sub> was synthesised in house, Li<sub>4</sub>Ti<sub>5</sub>O<sub>12</sub> was obtained  
from Hohsen Corporation Japan, TiS<sub>2</sub> was obtained from  
Alfa Aesar. The coatings were dried at 140 °C for about  
15 minutes, densified using a Durston rolling mill, and  
further dried overnight under dynamic vacuum at 80 °C.  
Finally, samples of 15 mm diameter, with a typical  
capacity of 1-2 mAh, were punched out and used for  
testing.

All measurement were done using CR2320 type coincells  
(23 mm diameter, 2 mm high, 304 steel, acquired from  
Hohsen Corporation Japan), with polypropylene (PP) or  
polytetrafluoroethylene (PTFE) gaskets, or in 304 steel  
cells with high temperature viton O-rings. All cells were  
assembled in a glovebox. Typically, a cell was made by  
stacking in a can: an electrode, a 21 mm diameter  
glassfiber mat (type GF/C, Whatman) , a gasket, 4-5 drops  
of electrolyte with a 1 ml polyethylene pipet, a 17 mm  
diameter lithium disk 0.38 mm thick (Chemetall), a 17 mm  
diameter pressing plate 0.2 mm thick, a 15 mm diameter  
wave-spring, and a cap which was insulated by tape. If  
necessary, the electrolyte was warmed to about 100 °C to  
reduce the viscosity. The cells were closed in a manual  
CR2320 crimping tool (Hohsen Corporation Japan).

#### Testing of batteries

The cells were cycled (subsequent charging and  
discharging) in air in climate chambers ( $\pm 0.1$  °C  
accuracy) using Maccor S4000 battery testers. The cells  
were subjected to various current densities, ranging from  
0.1 to 1.0 C-rate. Within a cycle the current was  
constant and equal for discharging and charging. The  
1 C-rate is here defined as the current needed to fully  
discharge the battery in 1 hour as calculated from the

mass of active material and its specific storage capacity. Thus, ideally a 0.1C-rate discharge lasts for 10 hours and a 2.0 C-rate lasts 0.5 hour.

EXAMPLE I:

5 "Testing at 110° of a rechargeable battery with a  $\text{Li}_4\text{Ti}_5\text{O}_{12}$  cathode, a lithium metal anode and an electrolyte comprising LiTFSA in  $\text{P}_{14}\text{TFSA}$ "

10 A coin cell was made according to the procedures described above.  $\text{Li}_4\text{Ti}_5\text{O}_{12}$  was used as the cathode material and PvdF as binder on an Aluminium current collector. The electrolyte was a mixture of LiTFSA dissolved in  $\text{P}_{14}\text{TFSA}$  in the molar ratio of 0.38:0.62. The cell was cycled 242 times between 1.0 and 2.0 V at 110 °C.

15 In the first 29 cycles the current was varied between 0.1 and 1.0 C. FIG. 2 shows the capacity for discharging and charging as percentage of the expected sample capacity. Very stable cycling behaviour of the battery was found with good rate capability and high efficiency.

20 The voltage curves in FIG. 3 show the typical voltage curve of  $\text{Li}_4\text{Ti}_5\text{O}_{12}$  versus lithium for the 7-th, 107-th and 207-th cycle for the same current density indicating that the active material did not change and did not loose its integrity.

25 EXAMPLE II:

"Testing at 110 °C of a rechargeable battery with a  $\text{Li}_4\text{Ti}_5\text{O}_{12}$  cathode, a lithium metal anode and an electrolyte comprising LiTFSA in  $\text{P}_{16}\text{TFSA}$ "

30 A coin cell was made according to the procedures described above.  $\text{Li}_4\text{Ti}_5\text{O}_{12}$  was used as the cathode material and PvdF as binder on an Aluminium current collector. The electrolyte was a 2.0 mol/kg mixture of

LiTFSA dissolved in P<sub>16</sub>TFSA. The cell was cycled 150 times between 1.0 and 2.0 V at 110 °C.

In the first 29 cycles the current was varied between 0.1 and 1.0 C. FIG. 4 shows the capacity for discharging and charging as percentage of the expected sample capacity. Very stable cycling behaviour of the battery was found with good rate capability and high efficiency.

EXAMPLE III:

"Testing at 110 °C of a rechargeable battery with a TiS<sub>2</sub> cathode, a lithium metal anode and an electrolyte comprising LiTFSA in P<sub>14</sub>TFSA"

A coin cell was made according to the procedures described above. TiS<sub>2</sub> was used as the cathode material and PvdF as binder on an Aluminium current collector. The electrolyte was a mixture of LiTFSA dissolved in P<sub>14</sub>TFSA in the molar ratio of 0.40:0.60. The cell was cycled 13 times between 1.8 and 2.5 V and 87 times between 1.5 and 2.5 V at 110 °C.

FIG. 5 shows the capacity for discharging and charging as percentage of the expected sample capacity. The lowering of the lower cut-off voltage increased the capacity substantially. Apart from some initial fading the cycling is fairly stable and with high efficiency. The voltage curves in FIG. 6 shows the typical voltage curve of TiS<sub>2</sub> versus lithium for the 50-th cycle.

EXAMPLE IV:

"Testing at 150 °C of a rechargeable battery with a LiCrTiO<sub>4</sub> cathode, a lithium metal anode and an electrolyte comprising LiTFSA in P<sub>14</sub>TFSA"

A coin cell was made according to the procedures described above. LiCrTiO<sub>4</sub> was used as the cathode material and PvdF as binder on an Aluminium current

collector. The electrolyte was a mixture of LiTFSA dissolved in P<sub>14</sub>TFSA in the molar ratio 0.05:0.95. The cell was cycled 238 times between 1.0 and 2.0 V at 150 °C. The current was varied between 0.1, 0.5, and 1.0 C.

FIG. 7 shows the capacity for discharging and charging as percentage of the expected sample capacity. Despite the very low salt content the rate capability was surprisingly good although lower than in the previous examples. The capacity faded almost linearly with about 20% over 238 cycles at the 0.5 C-rate level.

EXAMPLES I-IV demonstrate that the tested cells are suitable for use as rechargeable batteries at a high temperature of up to at least 150 °C.

The examples further indicate that suitable materials for use in the rechargeable batteries are:

- Li<sub>4</sub>Ti<sub>5</sub>O<sub>12</sub>, LiCrTiO<sub>4</sub>, and TiS<sub>2</sub> as active intercalation materials.

It is also believed that other known intercalation materials as for example LiFePO<sub>4</sub>, LiCoO<sub>2</sub>, LiNiO<sub>2</sub>, LiNi<sub>0.8</sub>Co<sub>0.2</sub>O<sub>2</sub>, LiMn<sub>2</sub>O<sub>4</sub>, LiNi<sub>0.5</sub>Mn<sub>1.5</sub>O<sub>4</sub>, Li<sub>7</sub>MnN<sub>4</sub>, and Li<sub>3</sub>FeN<sub>2</sub> can be used.

- Aluminium and stainless steel SUS304 as a current collector materials.

It is also believed that other materials as for example nickel, copper, gold, platinum, carbon, and graphite can be used as current collectors.

- PvdF and PMMA as binder materials.

It is also believed that other known binder materials as for example PTFE, PCTFE, ECTFE, ETFE, and FEP can be suitable binder materials.

- Carbon black and graphite as conductive additives.

It is also believed that instead or together with Carbon black and Graphite it is possible to use a metal foam or similar porous but electronically conductive structure, glassy carbon, or a metal powder as a  
5 conductive matrix in the electrodes. This can be an advantage in case Carbon black and/or graphite cause unwanted side reactions with other materials in the battery.

- porous glassfiber mat as separator material.

10 It is also believed that for example porous layers comprising  $\text{Al}_2\text{O}_3$ ,  $\text{MgO}$ ,  $\text{Li-}\beta\text{-Alumina}$  are suitable separator materials.

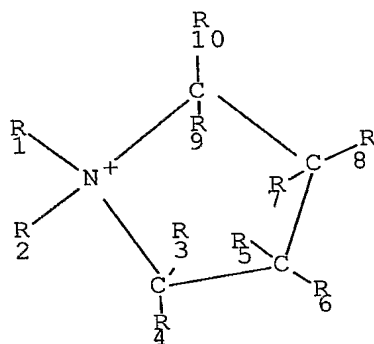
-  $\text{P}_{14}\text{TFSA-LiTFSA}$ ,  $\text{P}_{14}\text{TFSA-LiClO}_4$ , and  $\text{P}_{16}\text{TFSA-LiTFSA}$  mixtures as electrolytes.





C L A I M S

1. An electrochemical element with a cathode, an anode and an electrolyte arranged between the cathode and anode, which electrolyte comprises an ionic liquid comprising an anion and a cation, which cation has a  
5 pyrrolidinium ring structure,  
and wherein the active material of the cathode comprises an intercalation material.
2. The electrochemical element of claim 1, wherein the  
10 electrochemical element is a primary battery or a rechargeable battery or an electrochemical capacitor.
3. The electrochemical element of claim 1 or 2, wherein the electrochemical element is configured for use at a temperature above 50 °C.
4. The electrochemical element of claim 3 , wherein the  
15 electrochemical element is configured for use at a temperature between 60 and 200 °C.
5. The electrochemical element of any preceding claim, wherein the pyrrolidinium ring structure has the formula:  
N-R<sub>1</sub>-N-R<sub>2</sub>-pyrrolidinium, wherein R<sub>1</sub> and R<sub>2</sub> are alkyl  
20 groups.
6. The electrochemical element of claim 5, wherein the pyrrolidinium ring structure has the formula N-methyl-N-butyl-pyrrolidinium.
7. The electrochemical element claim 5, wherein the  
25 pyrrolidinium ring structure has the formula N-methyl-N-hexyl-pyrrolidinium.
8. The electrochemical element of claim 1, wherein the pyrrolidinium structure is:



wherein  $R_1$ - $R_{10}$  are either: H; F; separate alkyl groups which may be branched, substituted and comprise heteroatoms; separate phenyl groups which may be substituted and comprise heteroatoms.

- 5 9. The electrochemical element of any preceding claim, wherein the anion of the ionic liquid comprises any of the following compounds:

$\text{ClO}_4^-$ ,  $\text{PF}_6^-$ ,  $\text{BF}_4^-$ ,  $\text{AsF}_6^-$ , a halogen ion,  $\text{N}(\text{CF}_3)_2^-$ ,  $\text{N}(\text{CF}_3\text{SO}_2)_2^-$ ,  $\text{CF}_3\text{SO}_3^-$ ,  $\text{N}(\text{CH}_3\text{SO}_2)_2^-$ ,  $\text{N}(\text{C}_2\text{F}_5\text{SO}_2)_2^-$ .

- 10 10. The electrochemical element of claim 1, wherein the electrolyte further comprises a salt.

11. The electrochemical element of claim 10, wherein the salt comprises an alkali salt, particularly a lithium salt, more particularly a lithium salt comprising any of the following compounds:

15 -  $\text{LiN}(\text{CF}_3\text{SO}_2)_2$ ,  $\text{LiCF}_3\text{SO}_3$ ,  $\text{LiClO}_4$ ,  $\text{LiBF}_4$ ,  $\text{LiPF}_6$ , or  $\text{LiAsF}_6$ .

12. The electrochemical element of claim 10, wherein the salt comprises  $\text{MgCF}_3\text{SO}_2$  or  $\text{Mg}(\text{ClO}_4)_2$ .

- 20 13. The electrochemical element of any preceding claim, wherein the active material of the cathode comprises an intercalation material as the major constituent by mass.

14. The electrochemical element of claim 13, wherein the cathode comprises as the major constituent by mass of the active material any of the following compounds:
- 25

$\text{Li}_4\text{Ti}_5\text{O}_{12}$ ,  $\text{LiTi}_2\text{O}_4$ ,  $\text{Li}_{4-2y}\text{Mg}_y\text{Ti}_5\text{O}_{12}$  ( $0 \leq y \leq 0.1$ ).

15. The electrochemical element of claim 13, wherein the cathode comprises  $\text{LiCrTiO}_4$  as the major constituent by mass of the active material.

5 16. The electrochemical element of claim 13, wherein the cathode comprises  $\text{TiS}_2$  as the major constituent by mass of the active material.

10 17. The electrochemical element of claim 13, wherein the cathode comprises  $\text{Li}_{1-y}\text{M}_y\text{FePO}_4$ , where  $\text{M}=\text{Mg}$ ,  $\text{Nb}$ ,  $\text{Zr}$ ,  $\text{Ti}$ ,  $\text{Al}$  and ( $0 \leq y \leq 0.02$ ), as the major constituent by mass of the active material.

18. The electrochemical element of claim 1, wherein the anode comprises lithium metal as the major constituent by mass of the active material.

15 19. The electrochemical element of claim 1, wherein the anode comprises as the major constituent by mass of the active material any of the following compounds:  
 $\text{Li}_4\text{Ti}_5\text{O}_{12}$ ,  $\text{LiCrTiO}_4$ ,  $\text{LiTi}_2\text{O}_4$ ,  $\text{Li}_{4-2y}\text{Mg}_y\text{Ti}_5\text{O}_{12}$  ( $0 \leq y \leq 0.1$ ).

20 20. The electrochemical element of claim 1, wherein the cathode and/or anode comprises polyvinylidene fluoride (PVDF) as a binder material.

25 21. A method of providing electrical energy in an underground wellbore, wherein the energy is provided by an electrochemical element according to any preceding claim.

22. The method of claim 20, wherein the wellbore forms part of an oil and/or gas production well or a geothermal well.

30 23. The method of claim 21, wherein the wellbore forms part of an oil and/or gas production well and oil and/or gas is produced through the well and wherein the flow of oil and/or gas is monitored and/or controlled by electric downhole monitoring and/or control equipment which is

powered by an electrochemical element according to any one of claims 1-20.

A B S T R A C T

ELECTROCHEMICAL ELEMENT FOR USE AT HIGH TEMPERATURES

An electrochemical element for use at a high temperature has a cathode comprising an intercalation material as active material, an anode and an electrolyte arranged between the cathode and anode, which electrolyte comprises an ionic liquid with an anion and a cation, which cation comprises a pyrrolidinium ring structure comprising four Carbon atoms and one Nitrogen atom. Experiments revealed that rechargeable batteries comprising N-R<sub>1</sub>-N-R<sub>2</sub>-pyrrolidinium, wherein R<sub>1</sub> and R<sub>2</sub> are alkyl groups and R<sub>1</sub> may be methyl and R<sub>2</sub> may be butyl or hexyl, are particularly suitable for use at a temperature of up to about 150 degrees Celsius and may be used in oil and/or gas production wells.

(FIG. 1)



# Pyrrolidinium cations

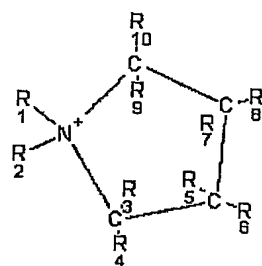


FIG. 1A

pyrrolidinium ring structure:

$R_1$ - $R_{10}$  is e.g. H, F, alkylgroup, etc.

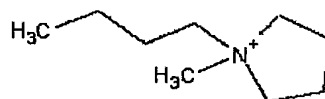


FIG. 1B

1-butyl-1-methylpyrrolidinium

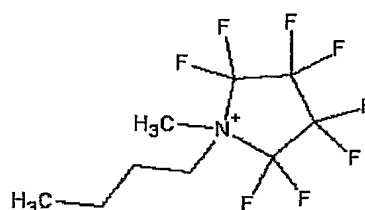


FIG. 1C

1-butyl-2,2,3,3,4,4,5,5-octafluoro-1-methylpyrrolidinium



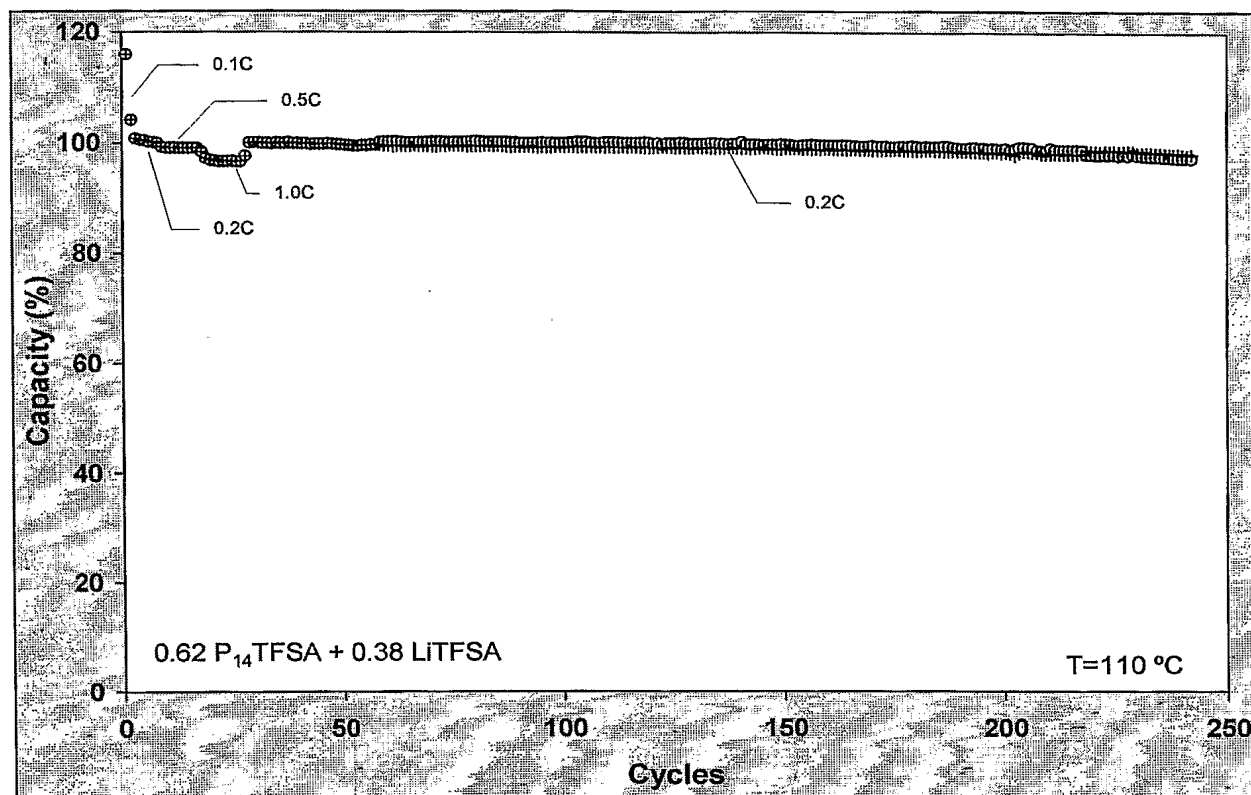


FIG. 2

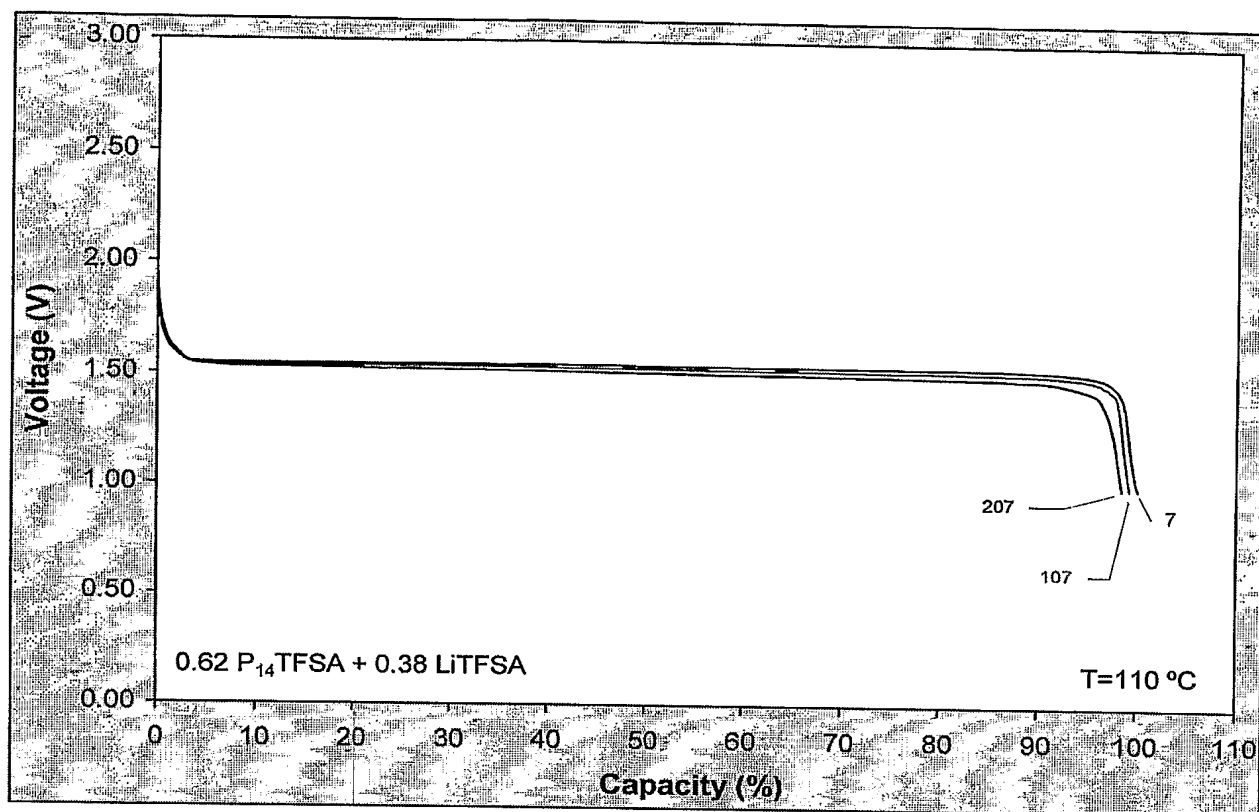


FIG. 3

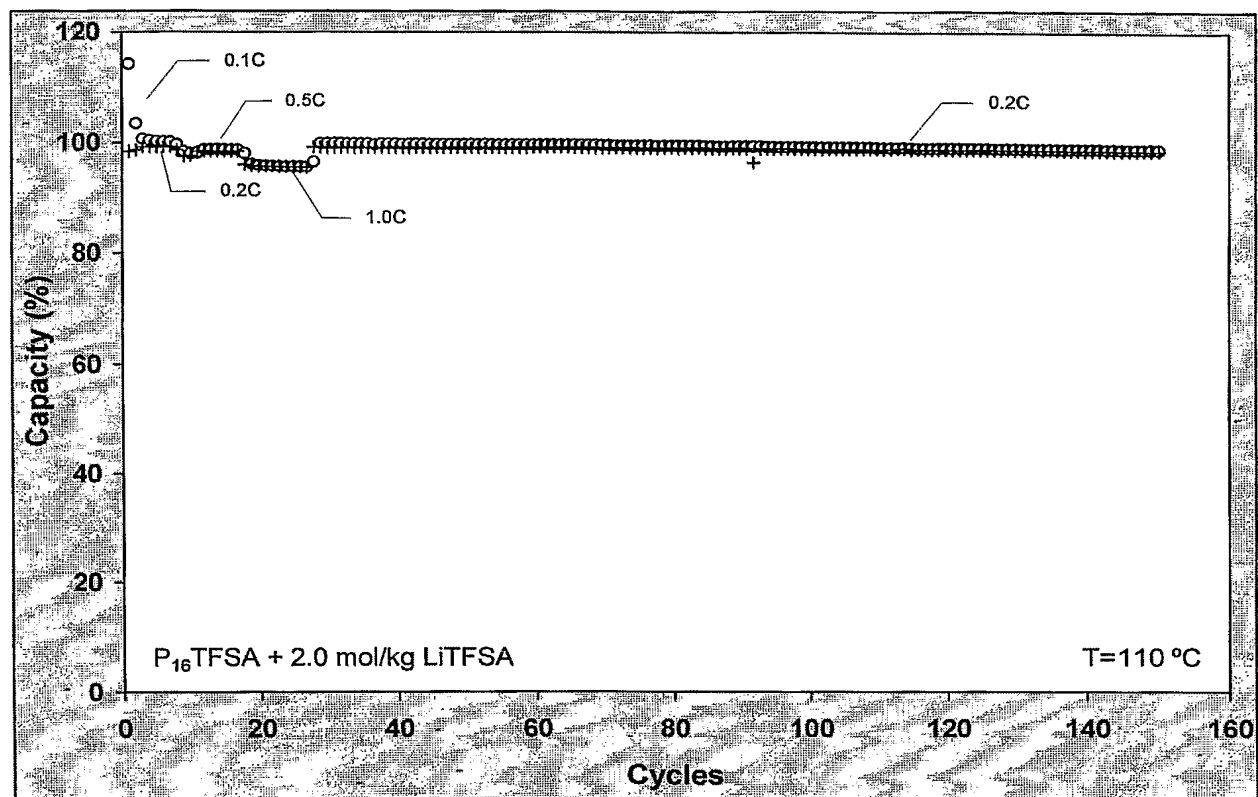


FIG. 4

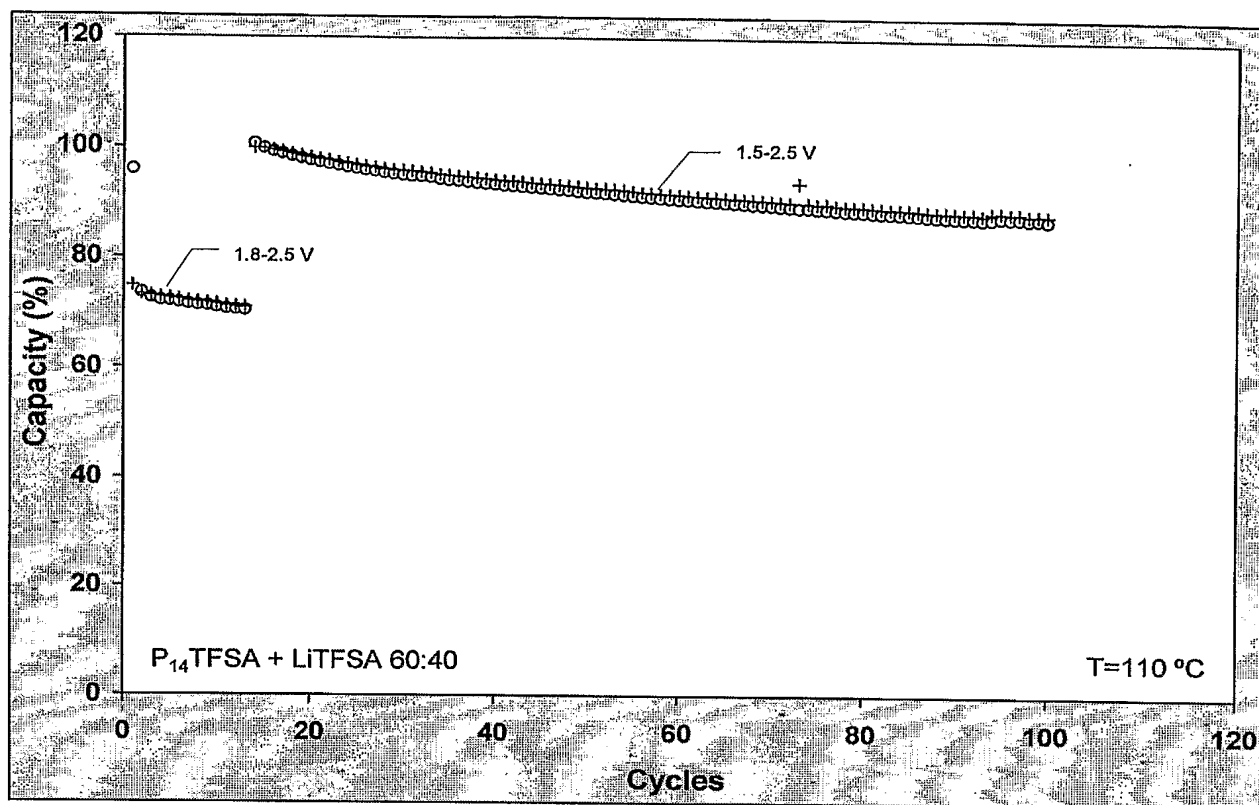


FIG. 5

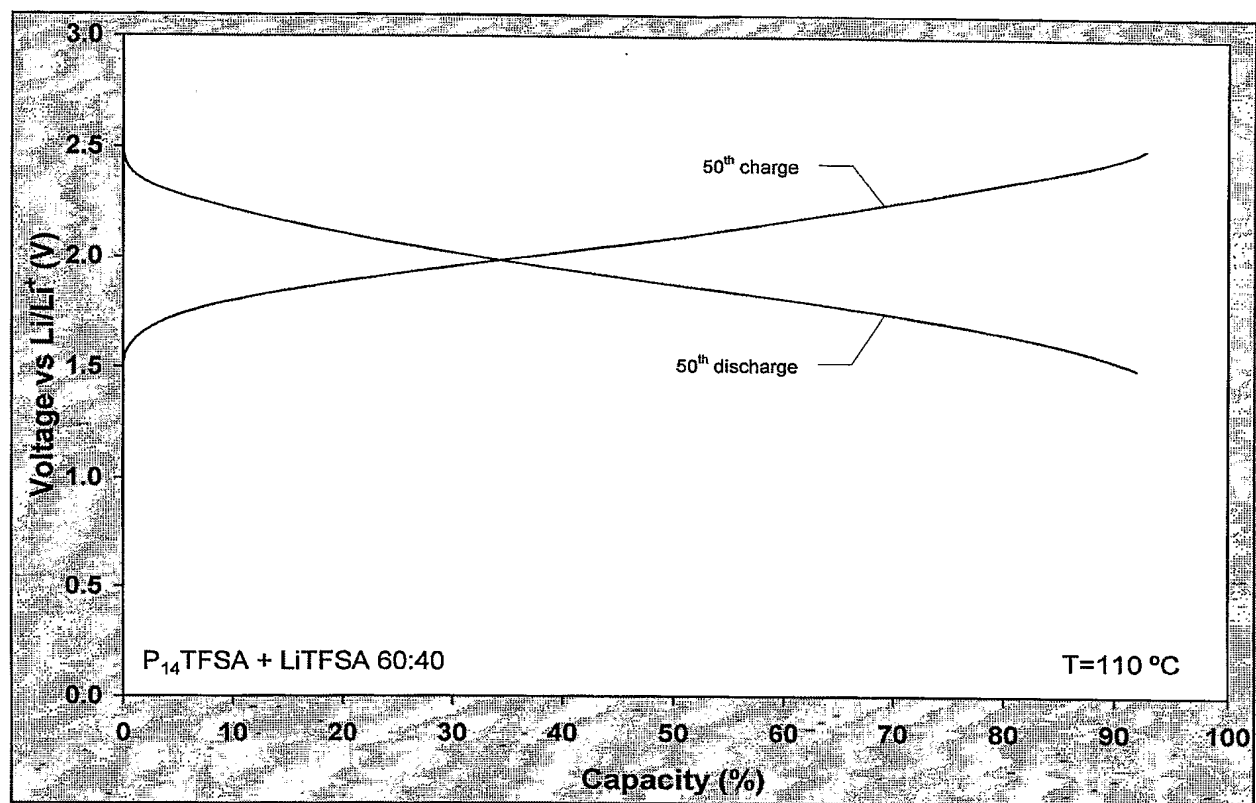


FIG. 6

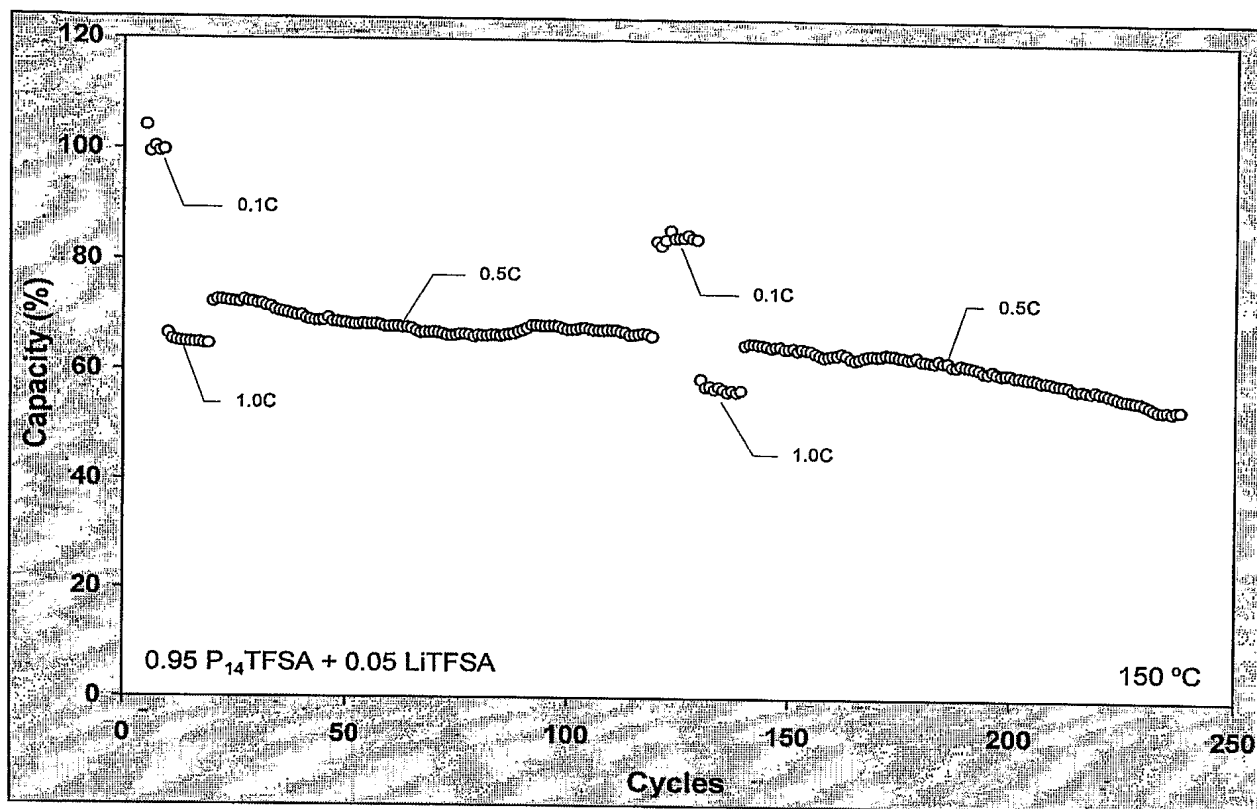


FIG. 7

